Detection Thresholds with Joint Horizontal and Vertical Gains in Redirected Jumping

Yi-Jun Li[1*] De-Rong Jin[1†] Miao Wang[1,2‡] Jun-Long Chen[1§]
Frank Steinicke[3¶] Shi-Min Hu[4‖] Qinping Zhao[1,2**]

1 State Key Laboratory of Virtual Reality Technology and Systems, Beihang University, China
2 Peng Cheng Laboratory 3 Universität Hamburg 4 BNRist, Tsinghua University, Beijing

Abstract

Redirected jumping (RDJ) is a locomotion technique that allows users to explore a virtual space that is larger than the available physical space by imperceptibly manipulating users' virtual viewpoints according to different gains. In previous redirected jumping work, different types of gains were imposed separately, without considering the possible interaction effects of horizontal and vertical gains on the jumping distance perception. To figure out how humans perceive distance manipulation when more than one gain is used, in this paper, we explored joint horizontal and vertical gains that manipulate horizontal and vertical distances at the same time during two-legged takeoff jumping in the virtual space. We estimated and analyzed horizontal and vertical detection thresholds by conducting a user study, fitting the data to two-dimensional psychometric functions, and visualizing the fitted 3D plots. We provided quantitative insights into the effects of joint gains on detection thresholds, where the imperceptible range for one gain can be affected by the variation of the other gain. Finally, we designed redirected jumping-based games as applications with joint horizontal and vertical gains and demonstrated the effectiveness of the redirected jumping technique.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality

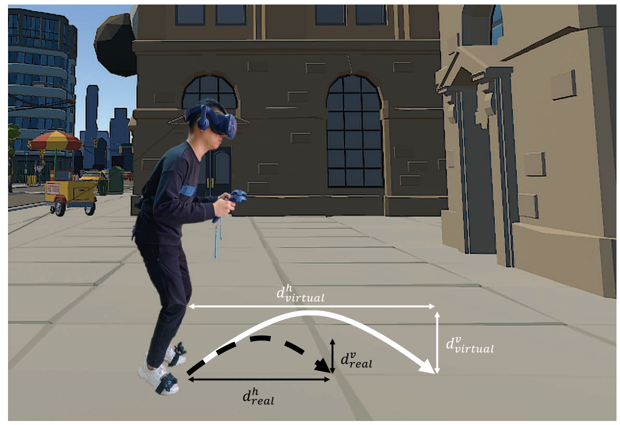

Figure 1: Illustration of redirected jumping with *joint horizontal and vertical gains*. A user performs two-legged takeoff forward jumping, where the physical *horizontal* jumping distance d^h_{real} and *vertical* jumping distance d^v_{real} are scaled as $d^h_{virtual}$ and $d^v_{virtual}$ correspondingly in the virtual environment.

1 Introduction

High-fidelity and free movements in virtual environments (VEs) are essential for many virtual reality (VR) applications, such as virtual sports and scene navigation. However, due to the limited size of the physical tracking space, travelling in the virtual space is always highly constrained to avoid hitting physical boundaries or obstacles. Therefore, effective locomotion techniques such as walking-in-place [20,26,27], teleportation [2,3,14], omnidirectional treadmills [8] and redirected walking (RDW) [14,21,24] were proposed to offer a better VR experience. Among these locomotion techniques, RDW provides users with a more intuitive and natural feeling of walking, which can greatly improve the sense of presence [25] and help users perform better in VR tasks [22]. The mechanism of most RDW methods is to manipulate users' virtual viewpoint by scaling the translation or rotation movement when they are walking in the VE, where the scaling factor is commonly called *gain*. Because the quality of the virtual experience is highly dependent on whether the rotation, translation, curvature, or bending gains [19] are imperceptible, a large number of studies on detection thresholds have been conducted in the VR community [12, 13, 16, 24, 28].

Recently, a new locomotion technique called redirected jumping (RDJ) that adjusts the virtual jumping properties, was proposed and investigated [6, 7]. When using this technique, users' virtual viewpoints are manipulated compared to their real-world movements according to the applied gains, including horizontal gains (scaling the jumping distance horizontally), vertical gains (scaling the jumping height vertically), rotation gains (scaling the jumping rotation angle) [7] and curvature gains (rotating the jumping direction when jumping forward) [9] during the jumping process.

However, most previous work measured such RDJ detection thresholds individually, without considering the potential effect of combined gains on detection thresholds. Improving our understanding of potential effects that influence the gain thresholds will enable effective settings of RDJ-based applications.

In this paper, we estimated detection thresholds with simultaneous *horizontal* and *vertical* gains in redirected jumping. Specifically, we conducted a user study with novel experiment settings with joint *horizontal* and *vertical* gains on two-legged takeoff forward jumps. To determine the horizontal and vertical detection thresholds, we collected pseudo-two-alternative forced-choice (pseudo-2AFC) responses from subjects and used such data to fit two-dimensional psychometric functions. With our experiment, we were able to estimate and model the detection thresholds as 2D continuous curves rather than discrete points that were used in previous work. We applied our findings in VR games, and demonstrated the effectiveness of the RDJ-based locomotion technique.

*joint first author, e-mail: yaoling@buaa.edu.cn
†joint first author, e-mail: jdrbuaa@buaa.edu.cn
‡corresponding author, e-mail: miaow@buaa.edu.cn
§e-mail: junlong2000@buaa.edu.cn
¶e-mail: frank.steinicke@uni-hamburg.de
‖e-mail: shimin@tsinghua.edu.cn
**e-mail: zhaoqp@vrlab.buaa.edu.cn

2642-5254/21/$31.00 ©2021 IEEE
DOI 10.1109/VR50410.2021.00030

2 Related Work

2.1 Redirected Walking

Due to the fact that the physical tracking space is often limited, it is often impossible to walk freely in large VEs. Therefore, many locomotion techniques such as teleportation [2, 3, 14], walking-in-place techniques [20, 26, 27] and RDW [14, 21, 24] are used to reduce the required physical space. Among them, RDW can offer a more natural moving experience than others because walking is the most frequent locomotion way in our daily life. When the user is walking in the VE, the RDW technique manipulates his/her point of view (PoV) by using rotation, translation, curvature [24] or bending manipulations [13], which are called *gains*. For example, the translation gain g_T can be defined as $g_T = d_{virtual}/d_{real}$, where $d_{virtual}$ stands for the translation distance in the VE and d_{real} represents the translation distance in the real world.

Besides creating virtual walking experiences on the flat ground, some RDW-based extensions were proposed. Marchal et al. [15] manipulated the viewpoint to make users feel like walking up and down in the VE, but actually, they were walking on the flat ground in the real world. Yamamoto et al. [30] built a VR system that applies pitch and roll re-orientation while virtual walking. Nagao et al. [17] proposed an interactive system using passive haptic feedback to make users feel as if they were ascending or descending stairs. RDW is also useful in telepresence systems, Zhang et al. [32] built a video-based 360° telepresence system using the RDW technique to change the motion mapping between the local environment and the remote environment, then measured imperceptible translation and rotation gain thresholds with user studies based on pseudo-2AFC tasks.

2.2 Redirected Jumping

Besides walking, bipedal jumping is also a common motion in our daily life. Sometimes it is more efficient than walking and can provide a more effective exploration of the VE [1, 29]. Through jumping, users can have access to various special experiences like ski jumping on an indoor apparatus [31], gravity reduced jumping on Lunar or Martian surfaces by using a cable-driven system [11], or even skydiving by using a Virtual Super-Leaping system [23].

Jumping is also important in redirection techniques. Hayashi et al. [7] proposed the RDJ concept and estimated detection thresholds of horizontal, vertical, and rotation gains with user studies. Results showed that the imperceptible gain for horizontal translation ranges from 0.68 to 1.44 and that for vertical translation is between 0.09 and 2.16. Jung et al. [9] measured the detection thresholds of curvature gains in RDJ. Both of these two studies showed that RDJ has a larger imperceptible gain range than RDW, which indicates that RDJ techniques can support VR experience in a larger virtual space. For RDJ applications, Havlík et al. [6] built a virtual factory scene where users can jump between moving platforms with an RDJ technique. A translation gain $g_T = 2.0$ was used for RDJ, which helped achieve a 30% reduction of physical tracking space without introducing discomfort to users. Matsumoto et al. [16] extended redirected vertical movements in jumping to redirected stretching and crouching movements while standing, and demonstrated that redirection techniques could imperceptibly manipulate the vertical movement both in VE and telepresence drone environment.

2.3 Effect Analysis on Detection Thresholds

Some previous work analyzed probable factors that affect the detection thresholds. It was revealed that under different conditions, detection thresholds can be different. Kruse et al. [12] studied the impact of the visibility of virtual feet and visual richness of VE on detection thresholds for translation gains in RDW. Their results showed that the visual richness has a larger impact than the visibility of feet representation on perceptual sensitivity of gains. Neth et al. [18] measured the detection thresholds of curvature gain under different walking velocities, and found that it was significantly easier for users to perceive the curvature manipulation when walking at a higher speed. Williams and Peck [28] conducted studies to estimate the rotation gain thresholds under different camera field-of-views (FoVs), gender, and distractor conditions and found significant differences between FoVs. There were also significant differences between genders when the FOV was equal to 110°. Besides, there was a wider range of detection thresholds for male participants with a 110° FOV. Grechkin et al. [5] investigated whether different translation gains can influence the user perception of curvature gain in RDW. According to their experiment results, there was no evidence supporting the hypothesis that curvature gain detection thresholds were affected by different translation gains. To the best of our knowledge, we are the first to analyze the joint horizontal and vertical gains in RDJ.

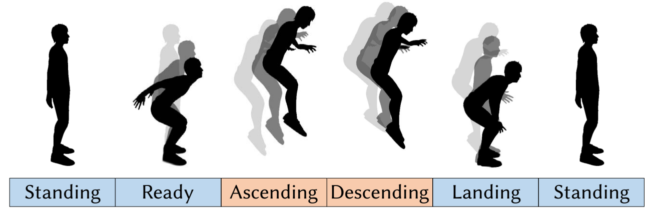

Figure 2: State division of forward jumping. Ghosting effects indicate the forward jumping motions. The manipulation of jumping distance is applied during the ascending and descending states.

3 Redirected Jumping with Joint Horizontal and Vertical Gains

In our experiments, users performed two-legged takeoff forward jumps, with horizontal and vertical jumping distances jointly manipulated by imposed gains in the VE. In this section, we introduce how the jumping distance was manipulated, the jumping state detection, as well as the overview of our experiments.

3.1 Jumping Detection

The manipulation of jumping distance is based on jumping state detection, with the assistance of the HMD, hand controllers and three trackers bound to the waist and feet to track real-time poses (see Figure 1). We adopted the jumping state detection algorithm from previous RDJ work [7, 9] that divided the jumping process into *standing*, *ready*, *ascending*, *descending* and *landing* states, see Figure 2. The manipulated horizontal and vertical gains were applied when the user was in *ascending* and *descending* phases. For more details of each jumping state, please refer to [7].

3.2 Jumping Distance Manipulation

Among various locomotion techniques, RDJ is now becoming a research hot spot. This technique was first proposed by Hayashi et al. [7] with the detection thresholds for horizontal, vertical and rotation gains of two-legged takeoff jumping measured by user studies. Following the definition from their paper, we let $d^h_{virtual}$ represent the horizontal jumping distance in the VE and d^h_{real} indicate the real horizontal jumping distance in the physical world, and the horizontal gain g_h is defined as:

$$g_h = \frac{d^h_{virtual}}{d^h_{real}}. \tag{1}$$

The vertical gain g_v is similarly defined, given $d^v_{virtual}$ representing the vertical jumping distance in the VE and d^v_{real} representing the vertical jumping distance in the physical world:

$$g_v = \frac{d^v_{virtual}}{d^v_{real}}. \tag{2}$$

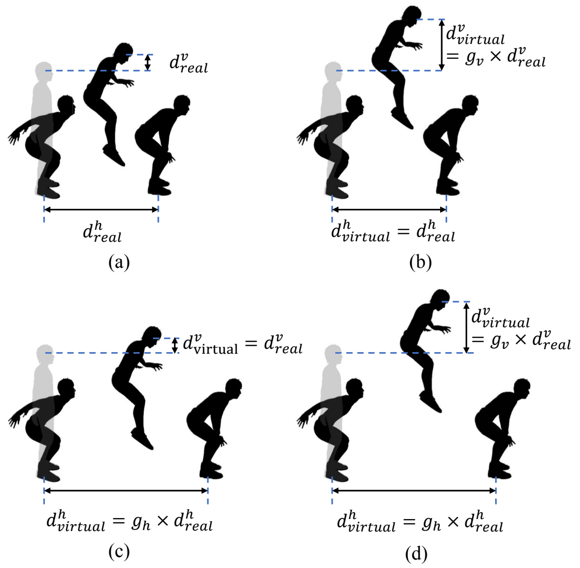

Figure 3: Illustration of RDJ. (a) An actual jumping action in the real world. (b) Vertically manipulated jumping with $g_v = 3.0$. (c) Horizontally manipulated jumping with $g_h = 1.5$. (d) RDJ with joint horizontal and vertical gains: $g_h = 1.5$ and $g_v = 3.0$.

For example, if the user jumped 1.0 meter forward physically with $g_h = 1.5$, he/she then performed a 1.5-meter forward jump in the VE, see Figure 3(a) and Figure 3(c). If the user actually jumped 0.2 meters in height with $g_v = 3.0$, he/she then experienced a 0.6-meter jumping height in the VE, see Figure 3(a) and Figure 3(b).

During the jumping process, the virtual jumping distance $d^h_{virtual}$ and height $d^v_{virtual}$ were scaled simultaneously under applied horizontal gain g_h and vertical gain g_v according to Equation 1 and Equation 2 by manipulating the user's virtual viewpoint, see Figure 3(a) and Figure 3(d).

4 Overview of Experiments

The goal of our research was to investigate how simultaneous horizontal and vertical gains affect the detection thresholds in two-legged takeoff forward jumping. We designed a user study to estimate horizontal and vertical detection thresholds which were visualized as continuous 2D curves, by applying simultaneous horizontal and vertical gain conditions. To this end, we collected responses to perceptual jumping distances via pseudo-2AFC tasks and statistically analyzed the data with two-dimensional psychometric function fittings. The pseudo-2AFC design has been used by many RDW and RDJ work [7, 12, 16, 18, 24], which applied a single stimulus and forced the participant to respond from two choices. Compared to the true 2AFC task that provides two distinct alternative stimuli for the response, such a pseudo-2AFC task although was designed to reduce bias from always choosing one of the two stimuli, may induce other bias, because both choices have expected a presentation of gain. Nevertheless, the pseudo-2AFC design was able to halve the experimental trials and physical load, especially in a long experiment.

We conducted another experience study in RDJ-based VR games. The player controlled an avatar using his/her own body in the first-person view and performed jumps to complete missions. Sampled gains within the estimated detection thresholds were used as gain conditions during jumping. We recorded the physical jumping performances as well as subjective responses for analysis.

5 User Study

This study employed a within-subject pseudo-2AFC design to evaluate the influence of *horizontal* × *vertical* gains on the perception of jumping distance manipulation along the horizontal or vertical direction. We asked subjects to perform two-legged takeoff forward jumps, with fixed horizontal ($0.8\,m$) and vertical ($0.1\,m$) distances in the virtual world, and experience RDJ with varied *horizontal* × *vertical* gains in a virtual city environment. The jumping distance was established by considering the physical load and task difficulty.

Following a pseudo-2AFC design to measure horizontal and vertical gain thresholds, after each jump, the participant needs to reply to two questions:

- **Q1:** Was the forward jumping distance in the VE longer or shorter than that in the real world?
- **Q2:** Was the jumping height in the VE higher or lower than that in the real world?

However, a pilot study revealed that it was challenging for the participant to simultaneously pay attention to horizontal and vertical manipulations during a jump. To solve this problem, we repeated jumping trials, and let the participant respond to **Q1** or **Q2** on different repetitions (denoted as Q1-repetition and Q2-repetition). With another pilot study, we determined the horizontal and vertical gain conditions as 5 horizontal gains varied from 0.5 to 1.5 in intervals of 0.25 and 5 vertical gains controlled from 0.333 to 3 at the square root of 3 logarithmic intervals, counter-balanced in random order, repeated 12 times (6 Q1-repetitions and 6 Q2-repetitions). In total, each participant completed 5 horizontal gains × 5 vertical gains × 12 repetitions = 300 jumping trials. With our experiment approved by the ethic committee of a local university, we carefully divided all trials into 3 sessions so that each participant took a session per day and finished the experiment in 3 successive days. Each session consisted of 2 Q1-repetitions and 2 Q2-repetitions of all enumerated gains, with a 10-minute rest between each repetition (25 trials). Participants could pause the experiment and have a rest once they felt uncomfortable.

5.1 Participants

We recruited 14 local university students (5 female, 9 male) from age 18 to age 22 (mean age: 20.50, SD = 1.29) to participate in this experiment. Before the study, we recorded the height of each participant (mean height: 172.36 [cm], SD = 8.13 [cm]). As for VR experiences, 6 of them had no experience, 5 had fewer than five experiences, and the rest had more than five. The participants were physically and mentally healthy enough to take part in this study.

5.2 Apparatus

The experiment was conducted in a lab with a $4\,m \times 4\,m$ (height: $2.7\,m$) physical tracking space. An HTC Vive Pro headset tracked by Base Station 2.0 provided 1440 × 1600 pixel resolution for each eye with a diagonal field of view of 110° at a 90Hz refresh rate. Two hand-held controllers were used to allow the participant to make choices in 2AFC tasks. Three trackers bound to the participant's waist and feet, together with the HMD and controllers, tracked the corresponding positions for jumping state detection. The tracked positions were visualized in real time as spheres in the VE. Major disturbances in the physical world such as environment noise were avoided during the experiment. Participants' safety was guaranteed by an experimenter so that he/she would not encounter danger in the real world.

The RDJ system was implemented in Unity3D (ver. 2019.4.8f1) with SteamVR and ran on a PC with Intel Core i7-9700KF 3.60GHz CPU, 32GB RAM and NVIDIA GeForce RTX 2080 Ti GPU. The POLYGON - City Pack virtual scene from Unity Asset Store was used as the VE. The virtual jumping position in the VE was chosen

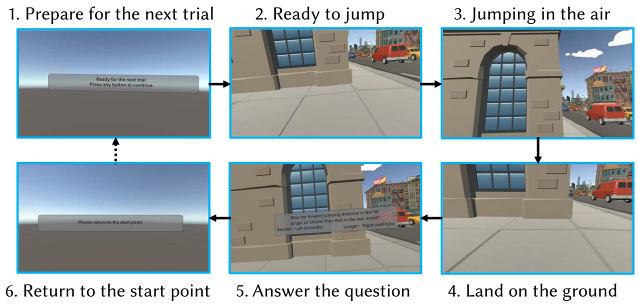

Figure 4: First-person view of a trial in the user study.

near a building (5 meters away), so as to provide users with enough visual cues to infer the jumping distance.

5.3 Procedure

After welcoming the participants into the lab, we introduced the goal, and process of the experiment to them. Each participant read and signed an informed consent form with a clear indication of the required health condition, then filled in a short demographic survey with their basic information.

Before each session, a pre-SSQ questionnaire [10] was filled out. We then helped the participant put on the devices and taught them how to use the controllers. A calibration stage recorded the positions of participants' heads, waists, and feet on a natural standing pose for jumping state detection. To better grasp the feeling of jumping with horizontal or vertical gains, in each repetition, the participant started with 8 training trials with known gains g_h and g_v and practiced answering questions with controllers. In the first 4 trials, $g_h = \langle 1, 0.5, 1, 1.5 \rangle$ and $g_v = 1$; in the last 4 trials, $g_h = 1$ and $g_v = \langle 1, 0.333, 1, 3 \rangle$. Intuitively, such a setting helped the participant perceive horizontal or vertical manipulations by comparing adjacent trials. In order to prevent the participant from remembering a fixed reference for distance estimation, each time entering the virtual scene, the participant's start position was horizontally randomized within a $2m \times 2m$. For each trial, the start and target indicators for jumping were shown on the ground. A translucent cube was located in the air, $0.1\,m$ higher than the calibrated HMD height, as a height indicator. Its color turned from blue to red once the viewpoint reached the cube's height. The participant was asked to jump from the start point and land at the target point, with his/her highest viewpoint equal to or higher than the cube's height. After landing on the ground, a UI appeared with question **Q1** or **Q2** which was answered using controllers. The scene then temporarily disappeared, leaving only the start indicator on the ground to guide the participant to return to the physical jumping position for the next trial.

Once the training trials were completed, the participant took formal trials of the current repetition. Different from previous training trials, jumping indicators in formal trials disappeared, but the participant was still asked to jump the same distance as in the training phase. Figure 4 illustrates the process of a jumping trial in the first-person view. Once all repetitions in a session were finished, the participant filled out a post-SSQ questionnaire, then left the lab and would come back in the next day to complete further sessions until all sessions finished. Each session of trials took about one and a half hours including the resting time. In total, each participant spent about four and a half hours, which we compensated with a voucher.

5.4 Results

5.4.1 Detection Thresholds

Based on previous studies, when *horizontal* and *vertical* gains are applied simultaneously, we define the *Lower Detection Threshold* (LDT) to be the horizontal gain where 25% of the responses to **Q1** were "Longer". Similarly, we define the *Point of Subjective Equality* (PSE) to be the value of g_h when 50% of the responses were "Longer" and the *Upper Detection Threshold* (UDT) when 75% of the responses were "Longer". *Vertical* detection thresholds are similarly defined based on the probabilities of "Higher" responses to **Q2**.

In psychophysical experiments, the goal of study is to regress the parameters Θ of some psychometric function $F(X, \Theta)$ mapping stimulus values X to the range $[0, 1]$. Previous RDW and RDJ gain threshold estimation work [7, 12, 24] fitted their collected pseudo-2AFC data with a one-dimensional psychometric function:

$$F(X, \Theta) = \sigma(\theta_0 + \theta_1 x), \tag{3}$$

with x being the gain value and σ the logistic function commonly used in regression problems:

$$\sigma(u) = \frac{1}{1 + e^{-u}}. \tag{4}$$

In our problem, because we explored horizontal and vertical detection thresholds with response data collected at two dimensions (simultaneous *horizontal* and *vertical* gains), instead of estimating *horizontal* detection thresholds for discrete *vertical* gains (or vice versa), we proposed to use a generalization of the 1-D psychometric function to two variables x_1 and x_2 which models the contribution of each variable and their possible multiplicative interactions, written as:

$$\dot{F}(X, \Theta) = \sigma(\theta_0 + \theta_1 x_1 + \theta_2 x_2 + \theta_{12} x_1 x_2 + \theta_{11} x_1^2 + \theta_{22} x_2^2), \tag{5}$$

where $\theta_0, \theta_1, \theta_2, \theta_{12}, \theta_{11}, \theta_{22}$ are constant function parameters [4].

We used a simple version of Equation 5 to regress function parameters Θ^{Longer} for the probability of responding "Longer" to **Q1**, and Θ^{Higher} for the probability of responding "Higher" to **Q2**:

$$\hat{F}(X, \Theta) = \sigma(\theta_0 + \theta_1 x_1 + \theta_2 x_2 + \theta_{12} x_1 x_2), \tag{6}$$

with x_1 being the horizontal gain, and x_2 the vertical gain. Compared to Equation 5, Equation 6 omitted the diagonal terms. This is because the coefficients of determination R^2 of Equation 5 (Θ^{Longer}: 0.9567, Θ^{Longer}: 0.9681) and Equation 6 (Θ^{Longer}: 0.9523, Θ^{Longer}: 0.9487) were very close when we fitted our collected pseudo-2AFC data, meanwhile Equation 6 involved less function parameters than Equation 5.

Figure 5 shows the pooled responses "Longer" to **Q1** or "Higher" to **Q2** at the same *horizontal* and *vertical* gain levels, and the fitted two-dimensional psychometric functions of horizontal and vertical responses (3D plots). Regressed function parameters are given in Table 1.

Viewing Figure 5 from the top, we plotted 2D figures (with clipped values between 25% and 75%) to illustrate the probability values within the detection thresholds, and highlighted curves that represent the LDTs, the PSEs and the UDTs, see Figure 6 (Left and Middle). Compared to one-dimensional psychometric function fitting which represented detection thresholds as discrete points, our estimated *horizontal* detection thresholds were continuous curves along the *vertical* gain axis, while the *vertical* detection thresholds were curves along the *horizontal* gain axis.

We reported the *Region of Interest* (ROI), a 2D region bounded by the *horizontal* and *vertical* LDT/UDT curves (denoted as LDT_h, LDT_v, UDT_h, and UDT_v respectively). Similar to the imperceptible range estimated by 1-D detection thresholds [7, 16], gain values inside the ROI were expected to be imperceptible. As an illustration, we computed several representative gain values at the intersection points (denoted as $P(LDT_h, LDT_v)$, $P(LDT_h, UDT_v)$, $P(UDT_h, LDT_v)$ and $P(UDT_h, UDT_v)$) along ROI boundaries, as shown in Figure 6. For example, the gains at the intersection point

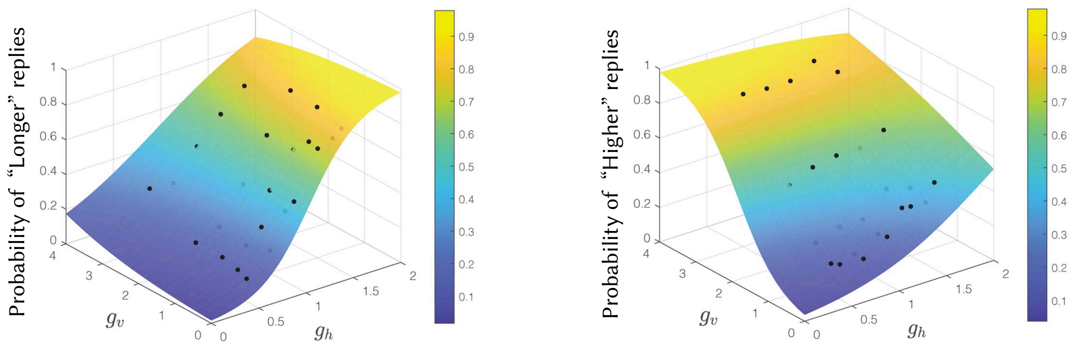

Figure 5: Plots of fitted psychometric functions. **Left:** probability of “Longer" replies to **Q1**. **Right:** probability of “Higher" replies to **Q2**, under *horizontal* $\times$*vertical* gain conditions. Pooled responses across participants are shown as black dots.

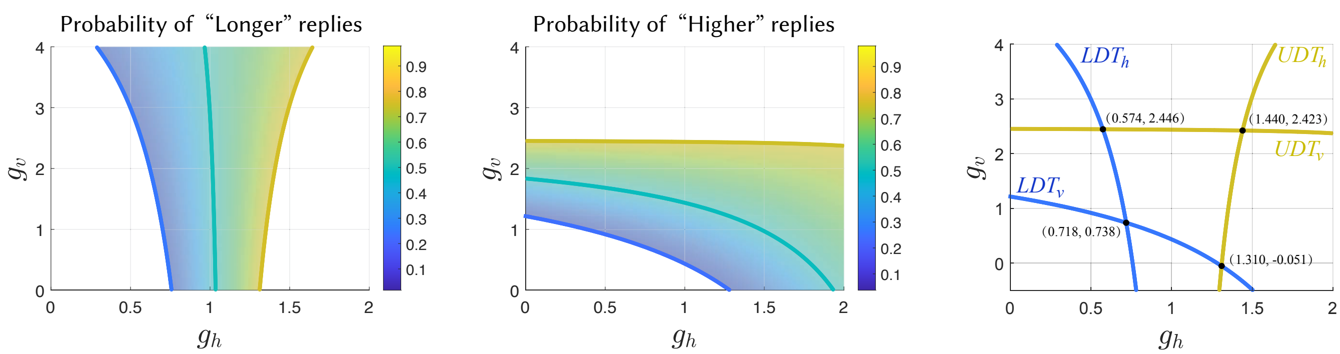

Figure 6: Detection thresholds. **Left:** probability of “Longer” replies, and *horizontal* detection thresholds; **Middle:** probability of “Higher” replies, and *vertical* detection thresholds. **Right:** the ROI and intersection points formed by detection thresholds. g_h stands for horizontal gain, and g_v stands for vertical gain. The blue, green and yellow curves represent the LDTs (25%), the PSEs (50%) and the UDTs (75%), respectively.

Table 1: Regressed two-dimensional psychometric function parameters for “Longer” (**Q1**) and “Higher” (**Q2**) responses.

	θ_0	θ_1	θ_2	θ_{12}
Θ^{Longer}	4.109	-3.971	-0.6368	0.5885
Θ^{Higher}	3.26	-1.685	-1.776	0.6797

$P(UDT_h, UDT_v)$ of the *horizontal* UDT curve and *vertical* UDT curve are $g_h = 1.440$, $g_v = 2.423$.

We further estimated each participant's detection thresholds at the intersections by fitting a two-dimensional psychometric function with his/her own responses and conducted significance tests based on the estimated individual detection threshold values. The data of participants was considered to have a bad fit and removed from the analysis if it was unable to fit the two-dimensional psychometric function with the coefficient of determination R^2 greater than 0.5. Kolmogorov-Smirnov tests and the inspection of Q-Q Plots revealed that the data was normally distributed. A paired t-test revealed a significant difference of *horizontal* gains between $P(LDT_h, LDT_v)$ and $P(LDT_h, UDT_v)$ ($p = .011$), and a significant difference of *vertical* gains between $P(LDT_h, LDT_v)$ and $P(UDT_h, LDT_v)$ ($p < .001$).

5.4.2 Simulator sickness

The SSQ total severity (TS) score averaged over all participants before and after each session was listed in Table 2. A Kolmogorov-Smirnov test showed that the data was not normally distributed. We analyzed the results with a Wilcoxon signed-rank test at the 5% significance level. For each session, we found that the SSQ TS score was significantly higher after the experiment ($p_{session_1} = .003$, $p_{session_2} = .001$, $p_{session_3} = .002$).

5.5 Discussion

The results showed that with a novel experiment setting and two-dimensional psychometric function regression, the horizontal and vertical detection thresholds could be estimated and modeled as 2D curves. By setting the *vertical* gain $g_v = 1.0$, the *horizontal* detection thresholds could be calculated as 0.70 for LDT, 1.03 for PSE and 1.35 for UDT, which were very close to the thresholds 0.68, 1.01 and 1.44 estimated by Hayashi et al. [7]. Once we finished setting the *horizontal* gain $g_h = 1.0$, we observed *vertical* detection thresholds of 0.38 for LDT, 1.48 for PSE and 2.57 for UDT. Compared to the vertical thresholds 0.09, 1.12 and 2.16 by Hayashi et al. [7], our *vertical* detection thresholds were slightly different. A possible reason for this was that the participants performed forward jumps in our experiment, while in Hayashi et al.'s study, the participants performed vertical jumps.

From the 2D detection threshold curves in Figure 6, we observed increased imperceptible horizontal gain ranges when increasing the vertical gain value, and increased imperceptible vertical gain ranges when increasing the horizontal gain value. This was statistically supported by the aforementioned significance tests on detection thresholds at intersection points of detection threshold curves. However, we did not find significant horizontal detection threshold changes along UDT_h or vertical detection threshold changes along UDT_v, within the ROI. This indicated that when combined *horizontal* and *vertical* gains were used, the perceptual sensitivity to LDT for one gain can be affected by the other gain. More specifically, the increasing g_h caused a significantly lower LDT_v and the increasing g_v led to a significantly lower LDT_h.

At intersection point $P(UDT_h, LDT_v)$, the vertical gain value was negative (-0.051). We clarify that this was because the nearby gains to $P(UDT_h, LDT_v)$ were $g_h = 1.25$ $g_v = 0.333$ and $g_h = 1.5$ $g_v =$

Table 2: Cybersickness ($Mean \pm SD$) before and after each session.

Sessions	Before	After
Session 1	2.939±1.672	13.891±4.302
Session 2	2.404±1.498	20.036±5.327
Session 3	3.473±1.638	20.303±4.361

0.333, where the response probability values both located within the vertical thresholds. On the other hand, this indicates that with an increased horizontal gain, the LDT of vertical gain is getting harder to be distinguished.

6 Application

Based on our findings, we developed two proof-of-concept VR games *BoxJumper* and *MarioMe* demonstrating the RDJ technique. The aim was to verify if the joint *horizontal* and *vertical* gains within the estimated thresholds could enhance or weaken the user's virtual jumping without catching his/her notice, and to explore the potential use of RDJ in virtual locomotion and rehabilitation.

6.1 Game Design

Both of the two games were based on the two-legged takeoff jump motion. The player controlled his/her virtual body with redirected jumping locomotion. A simple avatar was used, with the tracked joints represented as spheres.

BoxJumper: a game developed in a virtual farm scene (the POLYGON - Farm Pack Unity asset). The player starts the game standing on a virtual cubic wooden box (length of $0.5\,m$). In front of the current box is another box; the centers of the two boxes are horizontally $0.8\,m$ apart. The player's goal is to perform two-legged takeoff forward jumps and land on the center of the top surface of the next box. With a forward jump, if the player successfully lands on the next box (whether on the center or not), a box then appears with the same gap distance for the next jump. Otherwise, the player would come back for a retry. The player would complete the game after 8 successful forward jumps (4 sequential jumps $\times$ 2), see Figure 7 (Left). This game is designed to make the player focus more on his/her horizontal jumps.

MarioMe: a game developed upon the POLYGON - Dungeons Pack Unity asset. In the virtual scene, the player starts the game in a palace. By performing a two-legged takeoff forward jump with his/her head hitting a virtual treasure chest in the air (the nearest face of the chest is $0.3,m$ away from the player's head, and the bottom face of the chest is $0.2,m$ higher than the player's head), the player could collect a coin. After each successful hit, a new chest for the next jump would appear based on the player's current location. If the player fails to hit the chest with a forward jump, he/she would have to return to the previous location for a retry. The player would win the game by successfully collecting all 8 coins (4 sequential jumps $\times$ 2), see Figure 7 (Right). It is designed that the user pays more attention to vertical jumps so as to successfully hit the chests.

6.2 Experimental Design

As aforementioned, we would like to simultaneously apply *horizontal* and *vertical* gains that modify the horizontal/vertical jumping distances without being perceived by users. We used a between-group design that divided the participants into 3 groups $\{G_L, G_I, G_U\}$, and each group experienced both of the two games with a pair of *horizontal* and *vertical* gains. We chose the between-group design because each participant performed a sequence of jumps using fixed *horizontal* and *vertical* gains in each game. Since each participant experienced the same game with different gains, they could easily compare and distinguish the jumping distances.

Based on our findings in detection thresholds, we selected a pair of *horizontal* and *vertical* gains $g^L_{h,v} = (0.8, 0.8)$ within and near the

Figure 7: Representative frames of the RDJ-based games *BoxJumper* and *MarioMe*. The player's head, waist, hands, and feet are represented as spheres. He/she would perform two-legged forward jumps to complete tasks in the game. From Top to Bottom: the player is ready to jump, the player jumps in the air, and the player lands (please refer to the supplementary video for more details).

LDTs, and a pair of *horizontal* and *vertical* gains $g^U_{h,v} = (1.4, 2.0)$ within while near the UDTs. We also tested the gains $g^I_{h,v} = (1.0, 1.0)$ that did not manipulate the jumping as a control group. We recorded the horizontal jumping distances and subjective responses to **Q1** for the game *BoxJumper*, and recorded the vertical jumping distances and responses to **Q2** for the game *MarioMe*. This was because in a pilot study, we found that the users focused more on their horizontal jumps in *BoxJumper*, while in game *MarioMe* the users cared more about the vertical jumps.

6.3 Participants

30 participants were recruited to play the games, and were randomly divided into groups G_L (8M/2F, mean age = 22.40, $SD = 1.51$, mean height = 174.90 [cm], $SD = 8.61$ [cm]), G_I (8M/2F, mean age = 23.00, $SD = 1.25$, mean height = 174.10 [cm], $SD = 8.12$ [cm]) and G_U (8M/2F, mean age = 22.60, $SD = 1.27$, mean height = 172.60 [cm], $SD = 7.88$ [cm]). The participants in G_L, G_I or G_U played the games with gains $g^L_{h,v}$, $g^I_{h,v}$, or $g^U_{h,v}$ respectively.

6.4 Procedure

The gaming experience took place in a lab with a $6\,m \times 3\,m$ tracking area (height: $2.7\,m$). The equipment was the same as the previous user study. In each group, the participant played *BoxJumper* and *MarioMe* in random order. In each game, the participant completed 8 two-legged forward jumps to complete corresponding tasks. There was no strict time limit to complete the jumps, and the participant was allowed to take a short adjustment of a few seconds between neighboring jumps. After finishing *BoxJumper*, the participant responded to **Q1**, and once he/she completed *MarioMe*, **Q2** was replied. There was a 2-minute break between the two games.

Table 3: Averaging physical jumping distances and standard deviation values (in meters) in games *BoxJumper* and *MarioMe*, among testing groups G^L, G^I, and G^U.

Game	G^L	G^I	G^U
BoxJumper (horizontal)	0.775 ± 0.115	0.681 ± 0.075	0.550 ± 0.590
MarioMe (vertical)	0.290 ± 0.039	0.253 ± 0.038	0.133 ± 0.019

6.5 Results

The probabilities of "Longer" replies to **Q1** for the game *BoxJumper* among groups G^L, G^I and G^U were 0.5, 0.4 and 0.6, respectively. The probabilities of "Higher" replies to **Q2** for the game *MarioMe* were 0.5, 0.6 and 0.6, respectively. Because we sampled gain values within the detection thresholds, it was expected that the ratios of "Longer" responses to **Q1** or "Higher" responses to **Q2** were between 25% and 75%. Although a small number of responses were collected, we can observe that the responses of horizontal and vertical jumping distances were all within the expected range and around 50%.

Table 3 shows the average horizontal jumping distances for the game *BoxJumper* and the average vertical jumping distances for the game *MarioMe* as well as the standard deviation values. For the game *BoxJumper*, pairwise comparisons using independent t-test supported significantly different average values of horizontal jumping distances between G^L and G^I ($t(18) = 2.156, p = .044$), between G^I and G^U ($t(18) = 4.331, p < .001$), and between G^L and G^U ($t(13.401) = 5.510, p < .001$). For the game *MarioMe*, pairwise comparisons revealed significantly different average values of vertical jumping distances between G^L and G^I ($t(18) = 2.184, p = .042$), between G^I and G^U ($t(18) = 8.909, p < .001$), and between G^L and G^U ($t(18) = 11.396, p < .001$).

6.6 Application Summary

In the VR games where the RDJ technique was applied, the participants navigated the virtual scene and performed jumping to complete tasks in the game. By setting the *horizontal* and *vertical* gains within detection thresholds, it was proven difficult for the users to tell whether the jumping distances were manipulated. Meanwhile, the imposed gains indeed affected the user's physical performance. When the gain $g^U_{h,v} = (1.4, 2.0)$ was tested, the average horizontal jumping distances in the real world were significantly smaller than those from the control group $g^I_{h,v} = (1.0, 1.0)$. This adds significant weight to the idea that the RDJ technique enabled the user to explore a larger virtual space. On the other hand, under the condition $g^U_{h,v} = (0.8, 0.8)$ near the LDTs, the average physical jumping distances were significantly larger than those from the control group. This supported our previous findings that with small *horizontal* and *vertical* gains, RDJ has the potential to be used for exercise or rehabilitation to encourage the user to jump further or higher.

7 Discussion

Our measurement study computed the ROI formed by the detection threshold curves, where the imperceptible gain values can be chosen. As shown in Figure 6 of the measurement study, with increasing g_v, a larger horizontal UDT and a smaller horizontal LDT could be observed. One possible reason could be that most participants considered the ground or virtual objects on the ground as references. The higher they jumped, the smaller the objects they would perceive, which made them felt the horizontal movement not as obvious. Therefore, we can reduce the required physical tracking space for VR experience without users' perception by slightly increasing the vertical gain. We also observed that as g_h increased, the vertical LDT became smaller. This was probably due to the fact that once the participants jumped further, they expected to jump higher as well, but the content they saw along the vertical direction did not change as much. We observed significantly increased simulator sickness after each session. According to the observation and user comments, most of the increase was due to sweating and fatigue, suggesting that ways to improve the comfort level of the RDJ experience requires further investigation.

Based on the results of the game applications, a significantly smaller horizontal jumping distance (-0.131 m) could be observed in G^U compared to that in G^I, which confirmed that the RDJ technique under the condition in group G^U could effectively reduce the required physical tracking space. A similar conclusion could be drawn by comparing the physical jumping distance between G^I and G^L, which provides potential insights into rehabilitation exercises.

As mentioned in [7], RDJ can be naturally combined with RDW to further reduce the physical tracking space. Hence, we encourage VR developers to design VR applications by inducing more jumping actions to minimize the required physical tracking space. Regarding jumping actions, in our experiments, we only tested the standard two-legged takeoff jumps, so the measured detection thresholds may not extend to other kinds of jumping actions such as one-legged takeoff or continuous jumps. We argue, however, that the two-legged takeoff jump is an important locomotion method in VR applications like sports games, thus worth studying.

8 Limitations

Our work has a few limitations. First, with simultaneous *horizontal* and *vertical* gain conditions, we explicitly measured the horizontal and vertical detection thresholds with a pseudo-2AFC design. One may suggest investigating comprehensive detection thresholds that do not explicitly split to *horizontal* or *vertical* ones. While we argue that an understanding of detection thresholds for *horizontal* or *vertical* gains is important, we agree that comprehensive detection thresholds would be valuable, and regard it as future work.

Second, we acknowledge that bias exists in our experiments. In the pseudo-2AFC task, users were forced to choose from the biased "Longer/Shorter" options, even when no gain was applied. Moreover, we observed that the actual jumping distances were getting smaller as the experiment went on, which could introduce bias inadvertently.

Third, the application results were preliminary. We developed two proof-to-concept VR games that used the RDJ technique for locomotion. However, under strict epidemic prevention rules, we only successfully invited a small number of participants with a biased gender. A thorough demonstration study would be our future work.

9 Conclusion

In this paper, we introduced joint horizontal and vertical gains in RDJ. By designing pseudo-2AFC tasks on horizontally and vertically manipulated jumping distances, we collected response data at various horizontal and vertical gain levels which were good fittings to two-dimensional psychometric functions. We reported horizontal and vertical detection thresholds in the form of continuous curves along the gain axis and computed an ROI formed by those thresholds. We also found that the imperceptible range for the horizontal gain could be affected by the value of the vertical gain, and vice versa, which is novel and would benefit future research. We developed two RDJ-based VR games where horizontal and vertical gains were applied respectively, and obtained preliminary results regarding the usability of combined horizontal and vertical gains. Future work would include removing estimation bias, investigating safety issues when using this technique in a quite limited tracking space or outdoor scenes, as well as exploring the possibilities to comprehensively and naturally combine the RDW and RDJ-based locomotion techniques.

Acknowledgments

The authors wish to thank the anonymous reviewers for their helpful advices. This work was supported by the National Natural Science Foundation of China (Project Number: 61902012 and 61932003) and Baidu academic collaboration program. Frank Steinicke was supported by German Federal Ministry of Education and Research, German Research Foundation, the European Union's Horizon 2020 research and innovation program and the Federal Ministry for Economic Affairs and Energy.

References

[1] B. Bolte, F. Steinicke, and G. Bruder. The jumper metaphor: an effective navigation technique for immersive display setups. In *Proceedings of Virtual Reality International Conference*, vol. 1, pp. 2–1, 2011.

[2] E. Bozgeyikli, A. Raij, S. Katkoori, and R. Dubey. Point & teleport locomotion technique for virtual reality. In *Proceedings of the 2016 Annual Symposium on Computer-Human Interaction in Play*, pp. 205–216, 2016.

[3] F. Buttussi and L. Chittaro. Locomotion in place in virtual reality: A comparative evaluation of joystick, teleport, and leaning. *IEEE Transactions on Visualization and Computer Graphics*, 2019.

[4] C. DiMattina. Fast adaptive estimation of multidimensional psychometric functions. *Journal of Vision*, 15(9):5–5, 07 2015.

[5] T. Grechkin, J. Thomas, M. Azmandian, M. Bolas, and E. Suma. Revisiting detection thresholds for redirected walking: Combining translation and curvature gains. In *Proceedings of the ACM Symposium on Applied Perception*, pp. 113–120, 2016.

[6] T. Havlík, D. Hayashi, K. Fujita, K. Takashima, R. W. Lindeman, and Y. Kitamura. Jumpinvr: Enhancing jump experience in a limited physical space. In *SIGGRAPH Asia 2019 XR*, pp. 19–20. 2019.

[7] O. Hayashi, K. Fujita, K. Takashima, R. W. Lindernan, and Y. Kitarnura. Redirected jumping: Imperceptibly manipulating jump motions in virtual reality. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 386–394. IEEE, 2019.

[8] H. Iwata. The torus treadmill: Realizing locomotion in ves. *IEEE Computer Graphics and Applications*, 19(6):30–35, 1999.

[9] S. Jung, C. W. Borst, S. Hoermann, and R. W. Lindeman. Redirected jumping: Perceptual detection rates for curvature gains. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*, pp. 1085–1092, 2019.

[10] R. S. Kennedy, N. E. Lane, K. S. Berbaum, and M. G. Lilienthal. Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The international journal of aviation psychology*, 3(3):203–220, 1993.

[11] M. Kim, S. Cho, T. Q. Tran, S.-P. Kim, O. Kwon, and J. Han. Scaled jump in gravity-reduced virtual environments. *IEEE Transactions on Visualization and Computer Graphics*, 23(4):1360–1368, 2017.

[12] L. Kruse, E. Langbehn, and F. Steinicke. I can see on my feet while walking: Sensitivity to translation gains with visible feet. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 305–312. IEEE, 2018.

[13] E. Langbehn, P. Lubos, G. Bruder, and F. Steinicke. Bending the curve: Sensitivity to bending of curved paths and application in room-scale vr. *IEEE Transactions on Visualization and Computer Graphics*, 23(4):1389–1398, 2017.

[14] E. Langbehn, P. Lubos, and F. Steinicke. Evaluation of locomotion techniques for room-scale vr: Joystick, teleportation, and redirected walking. In *Proceedings of the Virtual Reality International Conference-Laval Virtual*, pp. 1–9, 2018.

[15] M. Marchal, A. Lecuyer, G. Cirio, L. Bonnet, and M. Emily. Walking up and down in immersive virtual worlds: Novel interactive techniques based on visual feedback. In *2010 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 19–26. IEEE, 2010.

[16] K. Matsumoto, E. Langbehn, T. Narumi, and F. Steinicke. Detection thresholds for vertical gains in VR and drone-based telepresence systems. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 101–107. IEEE, 2020.

[17] R. Nagao, K. Matsumoto, T. Narumi, T. Tanikawa, and M. Hirose. Ascending and descending in virtual reality: Simple and safe system using passive haptics. *IEEE Transactions on Visualization and Computer Graphics*, 24(4):1584–1593, 2018.

[18] C. T. Neth, J. L. Souman, D. Engel, U. Kloos, H. H. Bulthoff, and B. J. Mohler. Velocity-dependent dynamic curvature gain for redirected walking. *IEEE Transactions on Visualization and Computer Graphics*, 18(7):1041–1052, 2012.

[19] N. C. Nilsson, T. Peck, G. Bruder, E. Hodgson, S. Serafin, M. Whitton, F. Steinicke, and E. S. Rosenberg. 15 years of research on redirected walking in immersive virtual environments. *IEEE computer graphics and applications*, 38(2):44–56, 2018.

[20] N. C. Nilsson, S. Serafin, M. H. Laursen, K. S. Pedersen, E. Sikström, and R. Nordahl. Tapping-in-place: Increasing the naturalness of immersive walking-in-place locomotion through novel gestural input. In *2013 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 31–38. IEEE, 2013.

[21] S. Razzaque, Z. Kohn, and M. C. Whitton. *Redirected walking*. Citeseer, 2005.

[22] R. A. Ruddle and S. Lessels. The benefits of using a walking interface to navigate virtual environments. *ACM Transactions on Computer-Human Interaction (TOCHI)*, 16(1):1–18, 2009.

[23] T. Sasaki, K.-H. Liu, T. Hasegawa, A. Hiyama, and M. Inami. Virtual super-leaping: Immersive extreme jumping in vr. In *Proceedings of the 10th Augmented Human International Conference 2019*, pp. 1–8, 2019.

[24] F. Steinicke, G. Bruder, J. Jerald, H. Frenz, and M. Lappe. Estimation of detection thresholds for redirected walking techniques. *IEEE Transactions on Visualization and Computer Graphics*, 16(1):17–27, 2009.

[25] M. Usoh, K. Arthur, M. C. Whitton, R. Bastos, A. Steed, M. Slater, and F. P. Brooks. Walking> walking-in-place> flying, in virtual environments. In *Proceedings of the 26th Annual Conference on Computer Graphics and Interactive Techniques*, p. 359–364, 1999.

[26] J. D. Wendt, M. C. Whitton, and F. P. Brooks. Gud wip: Gait-understanding-driven walking-in-place. In *2010 IEEE Virtual Reality Conference (VR)*, pp. 51–58. IEEE, 2010.

[27] M. C. Whitton, J. V. Cohn, J. Feasel, P. Zimmons, S. Razzaque, S. J. Poulton, B. McLeod, and F. P. Brooks. Comparing ve locomotion interfaces. In *IEEE Proceedings. VR 2005. Virtual Reality, 2005.*, pp. 123–130. IEEE, 2005.

[28] N. L. Williams and T. C. Peck. Estimation of rotation gain thresholds considering fov, gender, and distractors. *IEEE Transactions on Visualization and Computer Graphics*, 25(11):3158–3168, 2019.

[29] D. Wolf, K. Rogers, C. Kunder, and E. Rukzio. Jumpvr: Jump-based locomotion augmentation for virtual reality. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, pp. 1–12, 2020.

[30] T. Yamamoto, J. Shimatani, I. Ohashi, K. Matsumoto, T. Narumi, T. Tanikawa, and M. Hirose. Mobius walker: Pitch and roll redirected walking. In *SIGGRAPH Asia 2017 Emerging Technologies*, pp. 1–2. 2017.

[31] N. Yoshida, K. Ueno, Y. Naka, and T. Yonezawa. Virtual ski jump: illusion of slide down the slope and gliding. In *SIGGRAPH ASIA 2016 Posters*, pp. 1–2. 2016.

[32] J. Zhang, E. Langbehn, D. Krupke, N. Katzakis, and F. Steinicke. Detection thresholds for rotation and translation gains in 360 video-based telepresence systems. *IEEE Transactions on Visualization and Computer Graphics*, 24(4):1671–1680, 2018.